Incentive Utilization model to avoid Localized Groundwater Overdraft

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Abstract— *Land subsidence caused by groundwater overdraft has been a severe problem in most developing economies, such as Taiwan. Groundwater is a renewable resource that can be depleted by overdraft, and it is also a common resource which incites overdraft. To alleviate the overdraft problem, we set up a decentralized game-theoretical common resource utilization model. In this model, we examine the self-enforcing factors and the condition of getting a cooperative outcome hence we might be able to alleviate the overdraft problem.*

Keywords*— *Common resource, Non-cooperative utilization, Overdraft, Renewable resource, Social optimum.

I. INTRODUCTION

Water is the most important resource for our survival, and it is also a widely misused resource on earth because of its abundant and renewable nature. Most developing and developed economies use groundwater when surface water is scarce or polluted. In some region, groundwater is the only water resource available in dry season or simply because of low annual rainfall. However, since groundwater can be renewed if used properly (that is, in a sustainable way), the economy might take nature's bountifulness for granted and overdraft. The problem of overdraft could be emanated from an incentive issue because groundwater is a common resource and the phenomenon of "the tragedy of the commons" (Hardin [3]) prevailed. For some communities, groundwater is a common pool resource, that is, all members of the community have access rights, and there's no legal restriction or option for the community to exclude the extraction of groundwater. And land subsidence is result of the groundwater overdraft. As a result, soil salinization and seawater intrusion severely hampered the economic progress of the coastal region of Taiwan, because the once fertile land became barren and hazardous even for homeowners to reside.

Groundwater overdraft happened when farmers and producers, from aquaculture, agriculture, or even the manufacture sector, that use the same source of groundwater (from the same aquifer) act non-cooperatively or selfishly. Selfishness or rationality assumption is a norm in most economic analysis. However, as described in McCarthy et. al [4], some communities do cooperate and manage their common pool resources successfully, albeit with costly rule-setting, monitoring, and enforcement mechanism. Much of the literature relied on centralized rule-setting and sanctioning power to enforce and to implement the mechanism, such as McCarthy et. al [4] and Coperland et. al [2]. But centralized authority might not be as effective as we assumed, as Agrawal [1] observed that "in the Kumaon region of the Indian Himalaya, villagers often set the forest on fire, because fire encouraged the production of fresh grasses, government attempts to prevent firing were always to remain a source of complaint". Although McCarthy et. al [4] recognized that "the threat of exclusion" is not possible and enforcing it is extremely costly, a community can act collectively and can manage their common pool resources efficiently, but their mechanism still rely on regulator's "explicit supervision and punitive action to enforce the cooperative agreement", while Copeland et. al [2] incorporate regulator's enforcement power into their framework directly. Even though they acknowledged that "poverty and government corruption" and international trade surely caused the misuse of common resources, their mechanism still needs an enforcer, i.e. the government. And their model assumed a "continuum of agents" that face a constant instantaneous probability of death, that is, the number of agents is infinite and they live in a continuous timeline. Although a continuum of agents and timeline is mathematically sound and impressive, but it is unrealistic and it will not solve our problem realistically. An infinite number of participants will cause a major free-rider problem, and a huge transaction cost. With a capable enforcer, the cost of supervision, sanctioning, and complying might be reduced to a tolerable level. But most modern government struggled just to get by, not to mention the fact that a modern government is a complex machine of legislation, lobbying, and regulating, public funding, and so on.

Our focus in this paper is the groundwater management of a small coastal community in Taiwan. Ostrom [6] found that a small community can better manage their common resources than a larger one, because the transaction costs is lower, while Olson [5] argued that cooperative agreement is easily complied and observed, because no action is anonymous in a small community, that is, no free-riding problem. In this paper, we develop a framework of a "decentralized" infinitely repeated game model to examine the outcome and to investigate the effect of some important factors. Just as the concluding remark in Agrawal [1], "The legitimation of authority occurs not through collective visions of dazzling development projects, but by the promise of meeting local needs indefinitely into the future if current consumption is restrained.". Our model is one step away from traditional mechanism framework, in the sense that we do not consider the "social planner" or government as the enforcer, but the community itself as a collective entity and members can negotiate and to agree or disagree (deviate). We will develop and characterize the decentralized game-theoretical model in section 2. The ensuing discussion will be in section 3. Section 4 is the conclusion.

II. THE MODEL

2.1 Characterization, Assumption, and Definition

We consider a small community of small farmers who need groundwater to support their economic needs. In a small community, everyone knows everyone's business, no one is protected from a nosey neighbor. Assuming every action is observable, so we can assume it is common knowledge. Since groundwater is a common pool resource, exclusion of access is quite difficult, and in fact, all members have access rights. We also assume that community members have long memories and unforgiving nature.

The decision process is an infinitely repeated game that can be depicted as a three-stage game: the first stage, the community get together and negotiate a "goodwill" or cooperative extraction level according to their projected production level. In the second stage, members of the community will decide whether they will comply or deviate from the cooperative agreement. If everyone complies in the second stage, they will maintain this choice till the end of the game. If anyone deviates, then none will cooperate again in the subsequent stages. So the third stage can be viewed as the original game starting from the third stage, and can be treated as a whole game, because it is infinitely repeated. This process can go on forever. The payoffs of this game can be characterized into three groups: the cooperative payoffs, the deviation payoffs, and the non-cooperative payoffs. We will discuss these payoffs in the following section.

Since it is a small community with small-sized farms, we can assume they are similar in their relevant economic characteristics. So we assume there are N identical farmers with the same capacity and ability to extract groundwater and produce crops. Note that N could be a "small" number. We adopt and modify Copeland [2] or Schaefer [7] model for harvesting, so the harvest (extraction) function for farmer i is the following

$$H_i = \alpha q_i S \tag{1}$$

where S denotes the resource stock level, α denotes a productivity parameter and $\alpha > 0$, and q_i denotes the size of the crop planted in the field by farmer i.

Adopting Copeland [2] model, the regeneration or natural growth function for the renewable resource (i.e. groundwater) is given by

$$G(S) = \beta S(1 - \tfrac{S}{K}) \tag{2}$$

where K denotes the carrying capacity of the resource stock, and β denotes the regeneration or growth rate of resource growth and $\beta > 0$.

Assume that groundwater is sufficient for the initial needs. Setting natural growth of groundwater in (2) equal to the total harvest (extraction) of groundwater in each period, i.e. ΣH, we will get the relationship between the resource stock S and total crop planted in the field in steady state:

$$S = K\left[1 - \tfrac{\alpha}{\beta} \sum q_i\right] \tag{3}$$

So if the total crop planted by the whole community (i.e. Σq_i) is greater than β/α, groundwater will dry up eventually. However if Σq_i is less than β/α, groundwater will not dry up. In this case, there is no need for the community to negotiate any cooperative extraction level.

Assume that the crop yields are sold in a competitive market with a relative price p. Farmer i's payoff (net benefit) function from his crop sale is the following:

$$\pi_i = pq_i - cq_i(\theta \sum H_i) \tag{4}$$

where c denotes the constant marginal cost of growing crops, and c > 0. We also include a depletion stress parameter, i.e. θ, which depicts the cost effect on the shock or distress of possible groundwater overdraft. If the total extraction or harvesting increases, the stress of extracting and using groundwater increases, therefore the cost increases. We assume $\theta \in [0,1]$.

The game-theoretical analysis follows the sequential rationality, that is, we plan ahead and take subsequent decisions and outcome into consideration when we make the decision. So we can apply the backward induction to unravel the optimal decision for every period or stage of the game. Note that the first stage is the collective negotiation phase, the payoff stream starts accruing from the second stage. Usually, we start the induction process from the last stage and then work through the stages backwardly until we reach the first stage of the game. The outcome for the third and the last stage depends solely on the outcome of the second stage, so we can focus our investigation on the second stage.

2.2 The Second Stage: Comply, disagree, or Deviate

In this stage, every farmer will choose to comply with the cooperative harvesting level or to deviate from it. We assume farmers are rational and choose whatever benefited them most. We will check the cooperative outcome, the non-cooperative outcome, and the deviation outcome, to see whether the farmer will comply, disagree, or deviate.

2.2.1 The Cooperative Outcome

The objective function of a cooperative negotiation for the community of N farmers is to maximize total payoffs for all the farmers:

$$\underset{\{q_i\}}{\text{Max}} \quad \sum(p - c\theta\alpha S \sum q_i)q_i \tag{5}$$

The first-order condition will solve for the cooperative crop plantation for each farmer:

$$q_i^* = \frac{1}{2N} \cdot \frac{p}{c\theta\alpha S} \tag{6}$$

The payoff for each farmer is:

$$\pi_i^* = \frac{1}{4N} \cdot \frac{p^2}{c\theta\alpha S} \tag{7}$$

2.2.2 The Deviation Outcome

To derive the non-cooperative outcome for a deviation, we assume other farmers are complying with the cooperative choice. The farmer will deviate if the payoff of the deviation (a windfall) is larger than the cooperative outcome. The objective function is the following:

$$\begin{aligned} &\underset{\{q_i\}}{\text{Max}} \quad \left[p - c\theta\alpha S\left(q_i + \frac{N-1}{2N} \cdot \frac{p}{c\theta\alpha S}\right)\right]q_i \\ &\text{s.t.} \quad q_j = q^* = \frac{1}{2N} \cdot \frac{p}{c\theta\alpha S}, \forall\, j \neq i \end{aligned} \tag{8}$$

The first-order condition will solve for the cooperative crop plantation for each farmer:

$$q_i^d = \frac{N+1}{4N} \cdot \frac{p}{c\theta\alpha S} \tag{9}$$

The payoff for each farmer is:

$$\pi_i^d = \left[\frac{(N+1)}{4N}\right]^2 \cdot \frac{p^2}{c\theta\alpha S} \tag{10}$$

Since $\left[\frac{(N+1)}{4N}\right]^2 > \frac{1}{4N}$, deviation gives the farmer a one-time windfall, because in the next stage no one will cooperate. The aftermath of the deviation will be the outcome of non-cooperative "punishment".

2.2.3 The Non-cooperative Outcome

After a deviation, no farmer will cooperate. each farmer will maximize his own payoff while assuming other farmers are using Nash strategy to make their equilibrium choices . The objective function is the following:

$$\begin{aligned} &\underset{\{q_i\}}{\text{Max}} \quad [p - c\theta\alpha S \textstyle\sum q_i]q_i \\ &\text{s.t.} \quad q_j = q_j^e \quad \forall j \neq i \end{aligned} \tag{11}$$

The first-order condition will solve for the cooperative crop plantation for each farmer:

$$q_i^e = \frac{1}{N+1} \cdot \frac{p}{c\theta\alpha S} \tag{12}$$

The payoff for each farmer is:

$$\pi_i^e = \frac{1}{(N+1)^2} \cdot \frac{p^2}{c\theta\alpha S} \tag{13}$$

Since $\frac{1}{4N} > \frac{1}{(N+1)^2}$, this means the cooperative payoffs is larger than the non-cooperative payoffs, thus the “punishment” for the deviation is the payoff degradation for the rest of the game. By comparing (7), (10), and (13), we can conclude that deviation payoffs is larger than cooperative payoffs, and cooperative payoffs is larger than non-cooperative payoffs, i.e. $\pi^d > \pi^* > \pi^e$. And from (1), (6), (9), and (12), we can also conclude that the deviator extract more groundwater than the non-cooperative outcome, and non-cooperative outcome extract more groundwater than the cooperative outcome, i.e. $q^d > q^e > q^*$.

2.2.4 To Deviate or Not To Deviate?

To know the answer, we need to calculate the payoffs for the third stage. There are three different payoff streams, that is, 1.) all members cooperate to the end, 2.) other members are cooperative and one member deviates, and 3.) all members disagree with each other and act non-cooperatively all the time. There are some subgames that would have member or members deviate in the 4th, 5th, or any other stages of the game, but once a member deviates, the rest of the game will be non-cooperative, and starting from that deviation, it is a deviation game with the deviation payoffs. The intrinsic nature of an infinitely repeated game is that every subgame can be treated just like the original game. What if more than one member deviates? The nature of sequential rationality is we make the best conjecture and act upon it. So if a rational member wants to deviate, he should wait for the opportunity to be the only deviator to get the most benefit from the deviation.

First, for the cooperative case, all members cooperate to the end. Assume that the discount factor is δ, and $\delta > 0$. The present value of payoff stream from second stage is the following:

$$PV(\text{coop}) = \frac{1}{4N} \cdot \frac{p^2}{c\theta\alpha S} (\frac{1}{1-\delta}) \tag{14}$$

Then, for the deviation case, since deviator earns more payoffs than non-deviator, we only consider the deviator’s payoff stream. The present value of payoff stream for the deviator is the following:

$$PV(\text{devi}) = \frac{(N+1)^2}{16N^2} \cdot \frac{p^2}{c\theta\alpha S} + \frac{\delta}{1-\delta} \frac{1}{(N+1)^2} \cdot \frac{p^2}{c\theta\alpha S} \tag{15}$$

Finally, for the non-cooperative case, the present value of payoff stream is the following:

$$PV(\text{none}) = \frac{1}{(N+1)^2} \cdot \frac{p^2}{c\theta\alpha S} (\frac{1}{1-\delta}) \tag{16}$$

From the present value listed above, we know that non-cooperative outcome is the worst outcome, which means that non-cooperation would seldom be the equilibrium choice in our decentralized common pool resource management study. Nonetheless, the choice to deviate is not so clear. The incentive for a rational farmer to deviate is getting more payoffs if he deviates. This can be shown by calculating the difference between the present value of deviation payoffs and the present value of cooperative payoffs. We can then divide this difference into two parts. First, let us consider the magnitude of the windfall derived from the deviation which is the difference between deviation payoffs and the cooperative payoffs, i.e. $\left(\frac{N-1}{4N}\right)^2 \frac{p^2}{c\theta\alpha S}$, and we can easily see that it is positive. So this part can be viewed as a reward for deviation. However, the second part of the “deviation incentive” is the difference between non-cooperative payoffs and the cooperative payoffs, i.e. $\frac{\delta}{1-\delta}\cdot\frac{-(N-1)^2}{4N(N+1)^2}\cdot\frac{p^2}{c\theta\alpha S}$, and it is obviously negative. So this part can be viewed as a punishment for deviation. When the punishment is sufficiently large enough to persuade a potential deviator to behave cooperatively, that is, if the punishment for deviation is larger than the reward of deviation, a rational farmer will not deviate. So for a rational member to be cooperative, the following condition has to be satisfied:

$$\frac{\delta}{1-\delta}\cdot\frac{1}{(N+1)^2}-\frac{1}{4N}\geq 0 \qquad (17)$$

III. THE EXOGENOUS FACTORS: COMPARE AND DISCUSS

Some exogenous factors could have important effect toward the analytical outcome. They could make or break a desirable outcome, such as cooperative result. We will discuss these factors in this section.

3.1 The Discount Factor

Discount factor is the weight that we put on future benefits and costs stream. It shows how the decision maker treats different time period. It also shows whether we are shortsighted or not. If discount factor is smaller, the decision maker is more shortsighted. If discount factor is larger, the decision maker is less shortsighted.

In (17) we got the condition for the cooperative outcome in the previous section without the government. Now we could examine the effect of a discount factor. If we differentiate (17) with respect to δ and held N constant, we will get a positive marginal effect, i.e. $\frac{\partial}{\partial\delta}\left(\frac{\delta}{1-\delta}\right)=\frac{1}{(1-\delta)^2}$, which means if δ increases, δ/(1-δ) will increase, and condition in (17) is more likely to be satisfied, that is, a potential deviator may change his mind and be more inclined to cooperate.

3.2 The Size of the community

With a small δ, condition in (17) is less likely to be satisfied, however the marginal effect of N is not as clearcut as the effect of δ. This is because larger community is easier for a deviator to hide among them. If the discount factor is getting smaller, people are more myopic, they put much less importance in future benefits or costs, and they care less about the future generation and prospect. But with a larger δ, people might care more about future benefits and costs, even with a large community, a large discount factor might change the behavior of a potential deviator.

3.3 The Human factor

Most of the assumptions and parameters in this paper are the economic factors, such as rationality and productivity parameter. There are some factors that are seldom mentioned and are important enough to change not only our perception of the world, but also our choices. For example, the villagers mentioned in Agrawal [1], they set the forest on fire in order to survive and had protested against the law, but their behavior gradually changed when government listened to the villager’s grievances and gradually letting local people manage and protect forests. These factors formulate the accepted actions and choices as a norm for the society. Most of us follow such norm as the social convention. These factors could have more affect in managing the common pool resource cooperatively than some economic policies and instructions.

One parameter in our model is closer to become a human factor than the others, that is, the stress parameter θ. If we care more about fellow members of our community, we might put more weight on the stress, that is, we care about not getting enough water for our field, but also our neighbors’ fields, then θ would be larger than the selfish one (i.e. the one that only reflect the stress about one’s field). From (6), (9), and (12), it shows that when θ increases, not only the cooperative choice of production will decrease, non-cooperative and deviation choices will also decrease. Hence, when we care more about our fellow members of the community, we might restrain our desire to overdraft.

IV. CONCLUSION

Our model shows that a decentralized mechanism is possible to construct and carry out as long as the conditions are met. For a small community with small holders, information is easily transmitted throughout the community, so a common knowledge framework and mechanism will get us the cooperative and self-enforceable result without government’s coercion or oversight. As long as members who have open access rights to the common pool resource are adequately caring and conform to the social norm of ethical behavior, the decentralized mechanism can be easily adopted and carried out.

Although under the assumptions in our model, we are free of the problem of transaction costs and the possibility of any free-rider. In reality, the problem can still occur even in a small community with a small group of holders. It is hard to ignore in the real world. There is mechanism to reveal the hidden action and information, thus remove the problem caused by free-riders. But the revelation mechanism is easily said than done. And it requires a more complex mechanism to achieve that goal. A complex mechanism is much harder to apply than a simple one in the real world.

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